Spacing interval between principal tree windbreaks

--Based on the relationship between windbreak structure and wind reduction

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Abstract: Relative windspeed reduction was measured behind nine relatively narrow, homogenous tree windbreaks with porosities between 0.13-0.33, and behind 28 combinations of model stubble barriers representing 25 different optical porosities (0.00-0.80). The optimum porosities observed were 0.25 and 0.13 for tree windbreaks and stubble barriers respectively. Based on the relationship between windbreak structure (optical porosity) and wind reduction, the chief indices for determining spacing interval, i.e., the windbreak structure index (δ) and the parameter of microclimate, represented by the problem wind (L_{rp}), were determined. Additionally, investigations on shelterbelt trees were carried out, and stem-analysis techniques were used, to develop a method for determining the mature height of tree windbreaks (H_0). Optimal spacing intervals between windbreaks could be predicted from the indices of a given windbreak structure, percentage of reduction of windspeed desired and tree growth model. A hypothetical example for determining the spacing interval of principal poplar windbreaks is given at the end of this paper. The results can be applied not only to tree windbreak design but also to other plant materials and artificial barriers for wind protection.

Key Words: Mature height; Optical porosity; Protected distance; Spacing interval; Shelterbelts; Windbreaks
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Introduction

The basic principles of wind control indicate that windbreaks planted or placed in the path of air flow act as surface barriers, causing an upward diversion of the air current (Woodruff 1956; Skidmore and Hagen 1977; Maki 1985; Zhu *et al.* 1998, 2001), and this diversion is accompanied by a drag on the wind at certain heights of the windbreaks. These combined effects lessen the force of wind on the original ground surface, lower the prevailing surface velocity (Zhu *et al.* 2000), and create an area of relatively calm airflow within the zone of influence of the windbreaks. This zone of influence is limited, extending leeward to a distance from several to more than 30 times the height of the windbreak (Woodruff 1956; Cao *et al.* 1981). However, the requirements for protection usually exceed this limited influence. In the case of windbreaks, protection can be achieved by establishing a system of properly oriented windbreaks. The most common design parameter for a system of windbreaks is the spacing interval (Cao 1983).

Many researchers (Woodruff 1956; Cao 1983; Tibke 1988; Ticknor 1988; Finch 1988) use the following simple equation to determine the spacing interval.

$$SIP = cH_0 \quad (1)$$

where SIP is the spacing interval for principal windbreak (m), H_0 is mature height of windbreak (m), and c is a constant, which is determined by the microclimate at the windbreak location and the type of windbreak.

However, few studies have quantified the magnitude of the constant c and mature height of tree windbreaks (H_0) because the relationships between these factors and wind are very complex (Cao 1983; Jiang 1992). It is usual to determine the constant c by considering just wind. Mature height is, on the other hand, estimated based on the experiences, or qualitative analysis by the designers. The effects of windbreak structure have not been considered in equation (1) at all, despite its obvious importance.

There are several aspects to the problem of determining the spacing interval for a system of shelterbelts. The principal reason for planting any shelterbelt is to reduce wind velocity. The amount and type of wind reduction needed, however, depend on the object to be protected and the purpose of the protection. Therefore, limiting the investigation to only one of these purposes does not completely solve the problem. For example, Woodruff (1956) found that to determine optimum spacing to control soil erosion, one must consider the susceptibility to erosion of the soil that is to be protected. This varies considerably by soil type and makes it difficult to prescribe a general formula for the velocity reduction required to control erosion. The object of this study was to develop quantitative criteria for the spacing interval of principal tree windbreaks for wind protection

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based on the mechanical reduction of windspeed, windbreak height, windbreak structure (optical porosity) and the microclimate related to the desired windspeed reduction.

Materials and methods

Study area

The experiments were conducted in the northeast of China, including several counties of Changtu, Liaoning Province; Nongan, Jiutai, Dehui, Shuangyang and Yushu, Jilin Province. The general situation of the shelterbelt site is a plain. Soil types are black soil, black meadow soil, black calcium soil and black sandy soil (Jiang 1992). The ages of shelterbelt range between 10 and 34; the rows of the shelterbelts are from 3 to 7. The observations of wind reduction for both tree shelterbelts and stubble barriers were conducted in Baoli Township and Zhujia Township, Changtu County, Liaoning Province.

Determination of independent variables

Although windbreak length, shape and width may influence the shelter effect leeward of windbreaks, tree height and windbreak porosity are more important (Cao 1983; Heisler and DeWalle 1988; Jiang 1992; Leoffler *et al.* 1992; Zhu *et al.* 2002). Therefore, mature height and porosity are considered as the key windbreak structural indices in determining spacing interval for wind control (wind protection). The additional major factor to influence windbreak effectiveness is the problem wind velocity because a reduction in momentum implies a reduction in velocity (Plate 1971). As described in equation (1), the constant c is mainly determined by microclimate and windbreak type. Thus, we defined the spacing interval for principal tree windbreaks as:

$$SIP = \delta L_{rp} H_0 \tag{2}$$

Here δ is the structure index (in this particular study, the structure of windbreak is represented by optical porosity), L_{rp} is a parameter of the microclimate, and determined by problem winds. The others are the same as mentioned above. If we assume δL_{rp}=c, equation (2) becomes equation (1). The purpose of this particular study is to determine quantitatively the three variables in equation (2).

Windbreaks with various porosities

The tree windbreaks were composed of poplar (*Populus* spp.), with average windbreak height varied from 8.0 m to 14.0 m, and the number of rows varied from 3 to 7 rows. Optical porosity (β) of tree windbreaks with leaves was obtained by using the digitizing techniques described by Kenney (1987) and Jiang (1989). This method required black and white photographic silhouettes of each tree windbreak, which was digitized to calculate windbreak optical porosity. The full height porosity was determined by the weighted mean of the bottom-half porosity and upper-half or crown-half porosity. Windbreak height was defined as the distance from the ground surface to the top of the tallest tree in the depicted windbreak segment. Nine shelterbelts were observed. The full height optical porosities for these tree windbreaks were 0.13, 0.15, 0.18, 0.20, 0.23, 0.25, 0.28, 0.30 and 0.33.

Reviews of the aerodynamics of barriers by Plate (1971) showed that the airflow patterns about wind barriers are very complicated. In the simplest case of a barrier normal to the airflow, the flow is turbulent (Hagen and Kidmore 1981). Barriers are usually within the so-called "constant-stress region" near the surface where the open field mean velocity profile is described by:

$$U_{mo}/U_* = (1/\kappa)\ln[(Z-D)/Z_0] + f(R_i) \tag{3}$$

Here U_{mo} is mean velocity at height Z, U_* is friction velocity, κ is von Karman's constant, Z is height of measurement from some reference plane, D is zero plane displacement height, Z_0 is a roughness parameter, $f(R_i)$ indicates that mean velocity also depends on Richardson's number (R_i), which is a measure of atmospheric stability. Under neutral stability, $f(R_i)$ is near 0 (Hagen and Kidmore 1981; Wang and Takle 1995, 1996).

From equation (3), it is obvious that both surface roughness and stability of the air influence airflow above barriers. In an atmospheric boundary layer with neutral stability, the airflow patterns near two geometrically similar barriers a and b will be similar in the following way:

$$(H/Z_0)_a = (H/Z_0)_b \tag{4}$$

Here H is windbreak or barrier height (Tanaka *et al.* 1955; Lyles and Allison 1976; Hagen and Kidmore 1981; Zhu 1981; Murai *et al.* 1992). This relationship means that model barriers that are shorter than the tree windbreaks can be used to increase the number of porosities in the study.

Model barriers with known height and optical porosity were constructed using one to seven rows of sorghum stubbles, which can be re-arranged freely. Porosities of a single row were 0.20, 0.40, 0.60 or 0.80. By varying porosity of individual rows and the number of rows, 28 different types of model barriers were produced, but because three combinations had similar porosity, only 25 kinds of porosities were obtained (Table 1). The maximum height of the stubble barriers was 1.85 m tall, and each barrier was 50 m long. The model barriers were established in the field, on a site that is flat in every direction for at least 2 km. The optical porosity of the stubble barriers was determined by a method of dotted grid, which was developed by George *et al.* (1963).

Windspeed measurements

Windspeeds and wind directions were measured by using 3-cup anemometers (528-MODEL and DEM-6 MODEL).

The instruments have a starting windspeed of 0.5 m•s^{-1} and 0.2 m•s^{-1}, respectively, and a maximum windspeed of 30 m•s^{-1}. One-minute average windspeed and direction can be read directly from the instruments. The errors of the instruments are ±0.2 m•s^{-1} and ±0.5 m•s^{-1} for DEM-6 MODEL and 528-MODEL, respectively. Both instruments are designed by Meteorological-oceanic Instrument Company, Tianjin, China. The arrangements for both tree windbreaks (DEM-6 MODEL) and the stubble barriers (528-MODEL) are as follows:

Table 1. Average optical porosity with various rows of model barriers*

Porosity of a single row	Rows 1	2	3	4	5	6	7
0.20	0.20	0.15	0.10	0.06	0.03	0.01	0.00
0.40	0.40	0.26	0.18	0.13	0.09	0.06	0.04
0.60	0.60	0.47	0.37	0.28	0.21	0.15	0.12
0.80	0.80	0.69	0.61	0.54	0.48	0.43	0.40

*Example: In the case of the porosity of a single row is 0.20; the composition of model barrier can be formed by 1 row, 2 rows, 3 rows, 4 rows, 5 rows, 6 rows and 7 rows. The optical porosities of the model barriers with 1 row, 2 rows, 3 rows, 4 rows, 5 rows, 6 rows and 7 rows are 0.20, 0.15, 0.10, 0.06, 0.03, 0.01 and 0.00, respectively. Three combinations produced the same porosity.

In the case of both tree shelterbelts and stubble barriers, for producing the open field values, one instrument was placed on the windward side at a distance not less than 20 times the heights of the windbreaks (one person all through read the wind data there during the observed period). The distances are expressed in terms of windbreak or model barrier height (H).

In the case of tree shelterbelt, the experiments were conducted during April and June (full leaf period of poplar shelterbelt). Windspeed and wind direction were collected at -10, -5, -3, -1, 1, 3, 5, 7, 10, 15, 20, 25 and 30 H at a height of 2.0 m above the ground; wind data at each point were observed simultaneously (Total 13 persons read the windspeed and wind direction at an interval of one minute at the same time). Data collection (significant data, i.e. wind blowing perpendicular to windbreak, and wind velocity more than 5 m•s^{-1}) of all anemometers lasted more than 10 min long at each point, and three repeats were conducted. The one minute average windspeed was in range of 6.0~8.4 m•s^{-1} in the field.

In the case of stubble barriers, the experiments were conducted during October and December, and windspeed and wind direction data were collected at -10, -5, -2, -0.25, 0.25, 5, 10, 15, 20, 25, 30 H from the stubble barriers at 0.5 m above the ground. Observations were also conducted at interval of one min, significant data collection lasted 5 min at each point, and three repeats were conducted. The one-minute average windspeed was during 5.0-13.0 m•s^{-1} in the field. Wind data at each point were not simultaneously observed because of lack of enough instruments.

Measurements were made only with winds blowing perpendicular to the tree windbreaks or the stubble barriers, and velocities over 5 m•s^{-1}. Average values of 5 min and 10 min for stubble barrier and tree windbreak respectively at per setting were used in the analysis.

Mature height for tree windbreak

Measurements on the growth of 118 field tree windbreaks were used to determine the mature height for tree windbreaks. Age, diameter (DBH) and height of four poplar species, *Populus xiaozuanrica, P. canadensis, P. simonii* and *P. pseudo-simonii*, were measured in the northeast China. Stem-analysis techniques were used in an age-height growth model for each species. About 80% of the tree shelterbelts are *Populus xiaozuanrica* (69) and *P. canadensis* (24), and 20% are *P. simonii* (14) and *P. pseudo-simonii* (11).

Both theory, with few exceptions, and empirical measurements have shown that the protected zone associated with a windbreak is directly proportional to the height of the windbreak (Tanaka *et al.* 1955; Caborn 1965; Cao 1983; Dronen 1988; Finch 1988; Ticknor 1988; Jiang 1994a). The height of non-living windbreaks is fixed with their materials by designers, but the height of tree windbreak changes with the growth of trees. Windbreaks are expected to provide permanent and complete wind protection, but it is known that the complete protection is not available for several, even several tens of years from the planting of windbreaks until they reach sufficient height to provide the complete protection.

Some researchers estimate the mature height of tree windbreak as the dominant height of mature windbreaks in best-adapted species for a given site qualitatively (Cao *et al.* 1981, 1983; Wight 1988; Jiang 1992). However, if the estimation of mature height is high enough, the spacing interval is too long for some tree species to provide the complete protection (Finch 1988). On the other hand, if the mature height is underestimated, the spacing interval for windbreaks is short enough, for the complete protection to be easily obtained at an early age. Complete protection will then quickly extend to the next windbreaks. Therefore, the mature height (H_0) is one of the key indices to obtain the optimum spacing interval. In this connection, "optimum" means smallest proportion of land devoted to tree windbreaks and the largest complete protection for the remaining land. The mature heights of tree windbreaks were determined from the investigations and growth development, that is, stem analysis techniques.

There is much information about tree height growth models, and the quantitative analysis of forest growth has progressed rapidly both in extent and in degree of sophistication (Jerome 1995). Previous studies about the growth of trees in shelterbelts (Jiang 1992; Zhu *et al.* 1992, 1996) indicated that the trees in windbreaks have their characteristics in growth because of the special site and edge effects for multiple-row windbreaks. Tree growth in most

shelterbelts can be well described using the following growth model:

$$H_i(t) = H_{ias}\{1 + \mu_i \exp[-\gamma_i(t - t_0)]\}^{-1} \quad (5)$$

where $H_i(t)$ is total growth of windbreak height (m), i represents tree species composed of the windbreaks, t is age of windbreak stand (year), t_0 is age at beginning (year), H_{ias} is asymptotic growth for a given tree species on a given site (m), μ_i is coefficient related to growth at a particular site and γ_i is internal incremental rate for a given tree species. The parameters in equation (5) were determined according to stem analysis.

Although relative growth rate and average growth rate are usually major indictors for division of tree growth stages, the incremental acceleration ($A_i(t)$) in growth rate is another important index for the growth stage division, particularly for the height growth (Husch *et al.* 1972). The incremental acceleration in growth rate in equation (5) is written as:

$$A_i(t) = H_i^{2}(t)/dt^2 = H_{ias}\mu_i\gamma_i^{2}\exp[-\gamma_i(t - t_0)]\{\mu_i \exp[-\gamma_i(t - t_0)] - 1\}\{1 + \mu_i\exp[-\gamma_i(t - t_0)]\}^{-3} \quad (6)$$

In equation (6), $A_i(t)$ has the minimum value in the following format.

$$A_{vi\,\min} = [\ln(\mu_i) + c]/\gamma_i \quad (7)$$

We found that the tree height of windbreaks would be relatively "stable" at age A_{vimin}, that is, the further growth of $H_i(t)$ after the age of A_{vimin} is relatively slow, thus, the effective protective distance is "relative stable" because the effective protective distance is direct proportion to $H^{8/7}$ (Tanaka *et al.* 1955). Therefore, we defined the height of tree windbreak at age of A_{vimin} as the mature height (H_0).

Results

Windspeed reduction with various porosities in tree windbreaks

Average windspeeds (three 10-minute averages) at each point are listed in Table 2. In this analysis only leeward data were used. The reduction of windspeed expressed by $1\text{-}U_{lee}/U_{open}$ (U_{lee}, U_{open} are windspeeds in leeward and open field respectively) in 0 to 10 H, 0 to 20 H and 0 to 30 H of tree windbreaks is shown in Fig.1. From Fig.1, the optimum reduction of windspeed was observed when tree windbreak porosity was around 0.25 for all distances leeward of the windbreak. However no significant difference between porosity 0.25 and the other various porosities can be found at level 0.01 by F-test.

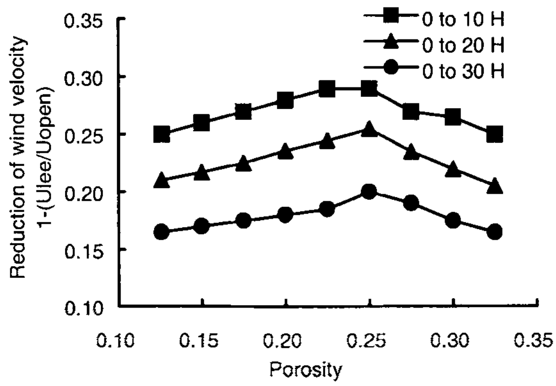

Fig. 1 Average windspeed reduction of tree windbreaks in leeward of 0 to 10 H, 0 to 20 H and 0 to 30 with different porosities,

(H is height of windbreak or model barrier, and some of the data were published in 1992, Jiang 1992)

Table 2. Average windspeed (Three 10-minute average) at the observed points of tree windbreaks with various porosities ($m \cdot s^{-1}$)*

Porosity	Row	-10H	-5H	-3H	-1H	1H	3H	5H	7H	10H	15H	20H	25H	30H	Field
0.13	7	8.14	7.76	7.65	7.35	7.57	7.42	6.49	5.53	4.99	4.81	6.24	7.06	7.61	7.98
0.15	4	7.69	7.11	6.83	6.52	7.27	7.25	6.03	5.28	4.60	4.40	5.71	6.53	7.21	7.54
0.18	7	8.62	7.96	7.64	7.29	8.15	8.12	6.73	5.88	5.11	4.89	6.38	7.30	8.07	8.56
0.20	4	8.53	7.92	7.69	7.02	8.00	7.82	6.37	6.07	4.98	4.50	5.00	6.98	7.88	8.38
0.23	4	5.95	5.45	5.21	4.95	5.56	5.55	4.50	4.04	3.48	3.29	4.22	5.02	5.55	6.02
0.25	4	7.07	6.15	5.81	5.32	6.42	6.71	5.06	4.89	3.98	3.87	4.88	5.94	6.66	7.07
0.28	5	7.38	6.65	6.06	6.13	6.95	6.95	5.42	4.96	4.51	4.17	5.53	6.39	6.89	7.40
0.30	3	5.75	5.29	5.06	4.82	5.39	5.38	4.41	3.97	3.45	3.27	4.14	4.89	5.38	5.62
0.33	5		6.75	6.63	6.44	7.05	6.92	6.36	4.60	4.16	4.22	6.35	5.88	6.62	6.99

*-10H, -5H, -3H, -1H: windward side of the shelterbelt; 1H, 3H, 5H, 7H, 10H, 15H, 20H, 25H, 30H: leeward side of the shelterbelt.

Windspeed reduction with various porosities in stubble barriers

Horizontal velocity measurements were made in each combination of porosity stubble barriers. Because the wind data at each point were not measured at the same time, the relative windspeed (U_{lee}/U_{open}) was used in this analysis. Mean ratios of leeward to windward windspeeds were computed from the cup anemometer at 0 to 5 H, 0 to 10 H, 0 to 15 H, 0 to 20 H, 0 to 25 H, 0 to 30 H and 0 to 35 H. The largest reduction of windspeed was observed in the stubble barriers with porosity of 0.13 (Table 3, Fig. 2). The stubble barriers with porosities in the range of 0.06 to 0.28 can provide better sheltering than the barriers with other porosities.

Table 3. Windspeed reduction by stubble barriers with various porosities (U_{lee}/U_{open})

No.	Porosity of single line	No. of row	Porosity	Upwind 10 H	Upwind 5 H	Leeward 5 H	Leeward 10 H	Leeward 15 H	Leeward 20 H	Leeward 25 H	Leeward 30 H	Leeward 35 H
1	0.20	1	0.20	0.84	0.74	0.29	0.36	0.46	0.53	0.60	0.64	0.68
2	0.20	2	0.15	0.84	0.76	0.18	0.27	0.37	0.45	0.52	0.58	0.63
3	0.20	3	0.10	0.84	0.76	0.20	0.31	0.41	0.48	0.55	0.59	0.65
4	0.20	4	0.06	0.80	0.71	0.19	0.31	0.39	0.47	0.53	0.58	0.63
5	0.20	5	0.03	0.81	0.72	0.21	0.32	0.41	0.48	0.54	0.60	0.65
6	0.20	6	0.01	0.84	0.75	0.26	0.36	0.45	0.52	0.58	0.65	0.69
7	0.20	7	0.00	0.86	0.77	0.28	0.38	0.46	0.54	0.61	0.66	0.72
8	0.40	1	0.40	0.92	0.88	0.51	0.54	0.60	0.65	0.70	0.73	0.77
9	0.40	2	0.26	0.85	0.79	0.25	0.31	0.40	0.48	0.54	0.59	0.63
10	0.40	3	0.18	0.86	0.80	0.16	0.27	0.37	0.45	0.52	0.58	0.63
11	0.40	4	0.13	0.82	0.76	0.13	0.24	0.35	0.43	0.50	0.55	0.60
12	0.40	5	0.09	0.83	0.76	0.17	0.29	0.38	0.46	0.53	0.58	0.63
13	0.40	6	0.06	0.83	0.76	0.17	0.28	0.37	0.45	0.52	0.57	0.62
14	0.40	7	0.04	0.86	0.79	0.22	0.34	0.42	0.49	0.54	0.59	0.64
15	0.60	1	0.60	0.92	0.89	0.58	0.65	0.71	0.76	0.80	0.83	0.85
16	0.60	2	0.47	0.90	0.87	0.41	0.47	0.54	0.60	0.65	0.68	0.72
17	0.60	3	0.37	0.87	0.83	0.32	0.39	0.47	0.54	0.59	0.63	0.67
18	0.60	4	0.28	0.88	0.84	0.25	0.34	0.43	0.50	0.57	0.62	0.66
19	0.60	5	0.21	0.84	0.78	0.23	0.33	0.42	0.49	0.57	0.60	0.64
20	0.60	6	0.15	0.88	0.81	0.22	0.31	0.41	0.49	0.54	0.52	0.62
21	0.60	7	0.12	0.87	0.82	0.23	0.35	0.44	0.51	0.57	0.62	0.67
22	0.80	1	0.80	0.89	0.88	0.82	0.83	0.85	0.87	0.89	0.90	0.91
23	0.80	2	0.69	0.87	0.86	0.71	0.73	0.76	0.79	0.81	0.82	0.84
24	0.80	3	0.61	0.89	0.86	0.71	0.71	0.74	0.77	0.79	0.82	0.84
25	0.80	4	0.54	0.88	0.86	0.66	0.68	0.70	0.72	0.75	0.77	0.79
26	0.80	5	0.48	0.88	0.86	0.59	0.62	0.66	0.70	0.73	0.75	0.78
27	0.80	6	0.43	0.88	0.84	0.54	0.59	0.64	0.69	0.72	0.75	0.78
28	0.80	7	0.40	0.90	0.87	0.53	0.57	0.63	0.67	0.71	0.74	0.77

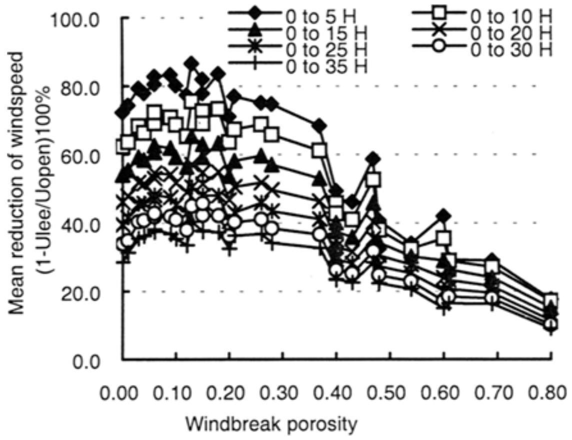

Fig. 2 Mean ratios of leeward to windward windspeeds of windbreak barriers with various porosities in different range of locations.

Mature height

The number of trees used for stem-analysis: *Populus xiaozuanrica*, 15; *P. canadensis*, 6; *P. simonii*, 5 and *P. pseudo-simonii*, 8, which were used to develop the age-height growth model in equation (5). The data from the model were compared with the field measurements, and no significant differences were found. The results of this analysis have been used in Changchun District, Jilin Province, China, and their reliability has been proven in a previous study (Jiang, 1996). The mature heights of four poplar species were determined according to equations (5), (6), and (7) and listed in Table 4.

Table 4. Determination of mature height (H_0) of poplar windbreaks

Tree species	Growth parameters H_{ias}	μ_i	γ_i	R^2	A_{vimin} /a	Mature height (H_0) /m
Populus simonii	17.9	8.16	0.159	0.828	23.5	13.4
P. pseudo-simonii	19.9	9.40	0.154	0.901	24.0	15.6
P. canadensis	25.7	5.80	0.206	0.867	15.0	20.3
P. xiaozuanrica	21.0	13.77	0.239	0.839	15.5	17.5

Generalized growth model is equation (4), A_{vimin} as defined in equation (6), R^2 is coefficient of determination, and each model was significant at p <0.01

Discussion

Structure index δ

Wind reduction is closely related to windbreak porosity, and classifying tree windbreaks on the basis of porosity would facilitate comparisons of effectiveness among tree windbreaks (Hagen and Kidmore 1971; Jiang *et al.* 1994b). The optimum aerodynamic porosity for field shelterbelts is usually considered to be 0.35 to 0.45 (Hagen and Kidmore 1971; Loeffler *et al.* 1992), but unfortunately, it is impossible to physically measure the aerodynamic porosity of field tree windbreaks. Much effort has therefore been directed towards finding alternative measurements. Optical porosity (β), a two-dimension measure of porosity determined from

the windbreak silhouette, may be a promising alternative to aerodynamic porosity. Heisler and DeWalle (1988) suggest that the optical porosity is a useful guide to windbreak functions, and therefore an appropriate guide for evaluating narrow windbreaks.

The optimum optical porosity has been studied by many researchers (Tanaka *et al.* 1955; George *et al.* 1963; Moysey and Mcpherson 1966; Hagen and Kidmore 1971, 1981; Zhou *et al.* 1991; Jiang 1992), but there is considerable variation in results. The source of this variation includes differences in shelterbelts structure, the effects of thermal instability in the field, the type of instruments used, the tree species, windbreak width, and the method used to determine the optical porosity. Despite this variation, most studies have suggested that the best sheltering is obtained using windbreaks with porosities of 0.20 to 0.50 (Moysey and Mcpherson 1966; Dronen 1988; Jiang 1992; Jiang *et al.* 1999).

The results in this experiment indicated that the optimum porosities measured in the tree windbreaks and in the stubble windbreak barriers were not consistent. Although similarity was retained between the two experiments using tree windbreaks and stubble barriers, we recognize that the stubble barriers do not react exactly like the tree windbreaks. Generally, under the tree windbreak conditions, the branches, twigs and leaves of trees move with the wind, i.e., the porosities of tree windbreaks are changing continuously with the wind velocity. However, the porosities of the stubble barriers seldom change, except with extremely strong winds. The tendencies of windspeed changes with different porosities around the optimum values (around 0.13 for the barriers, and 0.25 for the tree windbreaks) are very similar between the tree windbreaks and the stubble barriers (Fig.1 and Fig.2). These results, both from the tree windbreaks and the stubble barriers, are very similar to Moysey and Mcpherson's (1966). Those authors suggested that windbreaks with porosities in the range of 0.15 to 0.30 have better sheltering, and approximately 0.25 porosity is recommended for the best sheltering. Therefore, The regression relationship between windbreak porosity and windspeed reduction, namely, efficiency of windbreak in wind reduction changing with porosity, which was defined as structure index δ, can be obtained based on the observations of wind reduction from tree shelterbelts with combining the results from stubble barriers (Fig. 3). The multiple regression equation was:

$$\delta = 5.04249\beta^3 - 8.7712\beta^2 + 3.4239\beta + 0.6139 \quad (0 \le \beta \le 0.80) \tag{8}$$

$R^{2**} = 0.9339$, ** significant at $p<0.01$

Here β is windbreak porosity, it varies from 0.00 to 0.80, the range of value δ is from 0.31 to 1.00.

When $\beta=0.00$, $\delta=0.61$, when $\beta=0.80$, $\delta=0.31$ and when $\beta=0.25$, $\delta=1.00$.

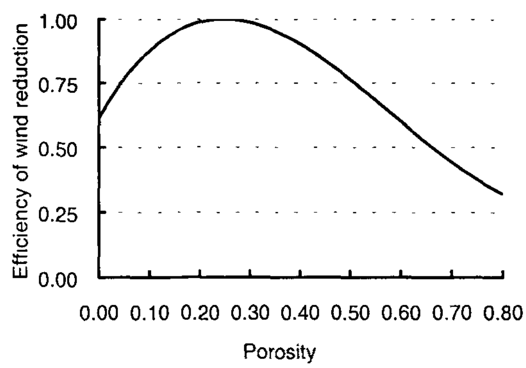

Fig. 3 Efficiency of windspeed reduction for field windbreaks with various porosities

(The best wind reduction is observed from a windbreak with porosity of 0 25)

Parameter of problem wind L_{rp}

The most frequent design requirement is that the wind be reduced below the dangerous level over a maximum distance. The reduction in wind velocity needed to protect objects from damage depends on the climatology of the approach wind conditions such as velocity of open wind, direction of problem wind and temperature, soil type and water content, the methods of tillage used and the situation of protected objects. The literature indicates that threshold velocity (threshold velocity defined as: velocity necessary to start movement of a soil particle or initially to damage the protected objects) is a key index for determining the effectiveness of windbreaks (George *et al.* 1963; Cao *et al.* 1981; Dronen 1988; Finch 1988; Wight 1988).

If problem wind velocity is V_{pw}, and the threshold velocity is V_{th} ($V_{pw}>V_{th}$), the reduction of windspeed U_{rw} can be written as:

$$U_{rw} = (V_{pw} - V_{th})/V_{pw}100\% = 100 - V_{th}/V_{pw}100\% \tag{9}$$

Based on the results of wind reduction under various porosities, the horizontal wind-profile with optimum porosity can be obtained as shown in Fig.4. The wind velocity reduction with the windbreak under the optimum porosity (0.25) from 5 to 35 H expressed as percentage of the open wind can be well described by a logarithm form as:

$$U_{lee}/U_{open} = \psi \ln(L_{rp}) + \phi_0 \tag{10}$$

where Ψ, Φ_0 are empirical constants, the others are the same as mentioned above.

In equation (10), L_{rp} is the only independent variable that significantly contributed to predicting the relative windspeed (U_{lee}/U_{open}), namely, the reduction of windspeed of problem wind (U_{rw}) is determined by L_{rp}. Therefore, integrating or combining equations (9) and (10), i.e., replacing V_{th}/V_{pw} with U_{lee}/U_{open}, the relationship regression is shown in equation (11).

$$U_{rw} = 100 - \psi \ln(L_{rp}) + \phi_0 \tag{11}$$

Solving equation (11) with the data from Fig.4, L_{rp} can be

written as:

$$L_{rp} = \exp[(130.3338 - U_{rw})/34.2176] \quad (12)$$

R^{2**}=0.9949, ** significant at p<0.01

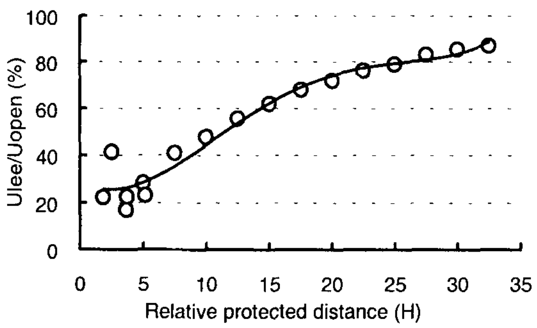

Fig. 4 Standard horizontal windspeed-profile of windbreaks with optical porosity of 0.25

It should be noted that the determination of the threshold velocities (V_{th}) for various protected objects is very complex, and equations (10) and (11) were obtained from the range of 5H to 35H of windbreaks or stubble barriers, therefore, the value of U_{rw} is limited between 9% and 75%. The range of U_{rw} is determined based on the calculation by equation (12). The result is only limited to wind protection, not including snow accumulation and other purposes.

Summary and conclusions

Field investigations were conducted to obtain information on the most important factors for determining the spacing interval. The results suggest that the average minimum wind reduction occurred in stubble barriers with 0.13 porosity (0 to 35 H), and tree windbreaks with 0.25 porosity (0 to 30 H). The stubble barriers with porosities in the range of 0.06 to 0.28 provide better sheltering than those with other porosities. The degree of efficiency of windbreaks depends not only on windbreak structure (optical porosity), but also on the type of protection desired or the problem winds. The influence of shelterbelt structure (optical porosity) upon leeward windspeed reduction is given by a multiple regression equation based on the observed results. Leeward relative windspeed reduction as an important sheltering characteristic was used to determine the parameters of structure index (δ) and problem wind (L_{rp}) for the spacing interval. The mature height of tree windbreak was also determined by developing a growth model of trees in windbreaks.

As a prerequisite to evaluating and comparing the spacing interval of the different porosity combinations of shelterbelts, it is necessary to establish desired levels of velocity reduction. As an example, levels of reduction of relative windspeed (U_{rw}) varying from 10% to 70% were chosen to calculate parameter of problem wind (L_{rp}). While these are only arbitrary levels based on the result of this particular study, one or the other should be appropriate for most wind velocity reduction problems. Porosities of windbreaks varying in some ranges of 0.1 to 0.45, 0.12 to 0.40, 0.15 to 0.36 and the optimum of 0.25 were chosen to calculate the structure index (δ). Mature heights (H_0) of four poplar species were given in Table 4 (Poplar shelterbelts). The results showing spacing intervals for the principal poplar windbreak are given in Table 5. All the results discussed were based on the measurements of windspeeds in plain farmland, the relationship examined are therefore not applicable to other disaster protection such as snow management.

Table 5. Spacing interval (SIP) for principal poplar tree windbreaks (m)*

Tree species	Range of porosity (β)	Average of Index (δ)	Reduction of relative windspeeds required U_{rw10}	U_{rw20}	U_{rw30}	U_{rw40}	U_{rw50}	U_{rw60}	U_{rw70}
Populus simonii	0.10 to 0.45	0.948	426.2	318.2	237.5	177.3	132.4	98.8	73.8
	0.12 to 0.40	0.966	434.3	324.2	242.1	180.7	134.9	100.7	75.2
	0.15 to 0.36	0.981	441.0	329.2	245.8	183.5	137.0	102.3	76.4
	Optimum 0.25	1.000	449.5	335.6	250.6	187.1	139.7	104.3	77.8
P.pseudosimonii	0.10 to 0.45	0.948	497.4	371.3	277.2	207.0	154.5	115.4	86.1
	0.12 to 0.40	0.966	506.8	378.4	282.5	210.9	157.5	117.6	87.8
	0.15 to 0.36	0.981	514.7	384.2	286.9	214.2	159.9	119.4	89.1
	Optimum 0.25	1.000	524.6	391.7	292.4	218.3	163.0	121.7	90.9
P. canadensis	0.10 to 0.45	0.948	646.8	482.9	360.5	269.1	200.9	150.0	112.0
	0.12 to 0.40	0.966	659.0	492.0	367.3	274.2	204.7	152.9	114.1
	0.15 to 0.36	0.981	669.3	499.7	373.0	278.5	207.9	155.2	115.9
	Optimum 0.25	1.000	682.2	509.3	380.3	283.9	212.0	158.2	118.1
P. xiaozuanrica	0.10 to 0.45	0.948	558.6	417.1	311.4	323.5	173.6	129.6	96.7
	0.12 to 0.40	0.966	569.3	425.0	317.3	236.9	176.9	132.0	98.6
	0.15 to 0.36	0.981	578.1	431.6	322.2	240.6	179.6	134.1	100.1
	Optimum 0.25	1.000	589.3	440.0	328.5	245.2	183.1	136.7	102.0

*Spacing interval (m) is from equation (2), δ defined as equation (8), U_{rw10} to U_{rw70} are the values of reduction of relative windspeeds required, U_{rw10} to U_{rw70} represent 10% to 70% reduction of relative windspeeds, L_{rp} is obtained from equation (12) by using U_{rw10} to U_{rw70}; mature height (H_0) is from Table 2.

Considerable further study is needed to determine the threshold velocities for various protected objects. The study reported here is indicative that spacing interval (SIP) is directly related to relative windspeed reduction (U_{rw}), but

not the threshold velocity.

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